CHAPTER 6

ADAPTIVE HYSTERESIS CURRENT CONTROL OF DC-AC INVERTER IN A GRID CONNECTED PV SYSTEM

6.1 INTRODUCTION

The previous chapters have discussed the development of the MPPT algorithm and the control of the DC-DC converter in a standalone PV system. A grid-connected PV system is composed of a photovoltaic array, DC-DC converter, DC link capacitor, single phase DC-AC inverter, filter inductor, power grid, and non-linear load. The grid interconnection of a PV power generation system has the advantage of more effective utilization of the generated power. The Grid interconnection of PV systems is accomplished through the inverter. The Grid-connected inverter is the critical interface of a photovoltaic array connected with the power grid. Pulse width modulation (PWM) is the most popular control technique in voltage-source inverters. Compared to the PWM converters, the current-controlled PWM has several advantages. It has lesser distortion and lower harmonic noise. This chapter deals with the development of adaptive hysteresis current control techniques for the DC-AC inverter, in order to provide a constant switching frequency with less harmonic content. The simulation results obtained, using the proposed current control technique, are presented. The hardware implementation of the proposed inverter current control algorithms using Xilinx spartran-3 FPGA, is also presented.
6.2 GRID CONNECTED SOLAR PV SYSTEM

Figure 6.1 (a) Block diagram representation of a grid connected PV system, (b) Schematic diagram of the grid connected PV system

Figure 6.1(a) shows the grid connected PV system. Figure 6.1(b) shows the schematic diagram of a grid connected PV system along with various controllers. The presented system consists of PV modules, a DC-DC converter, DC link capacitor, DC-AC converter, MPPT controller, Adaptive hysteresis current controller, PWM controller, and a grid. The solar photovoltaic array produces electricity when the photon of sunlight strikes the PV cell array. The output of the PV panel is directly connected to the DC-DC boost converter, to step up the DC output of the photovoltaic panel and to perform the MPPT. The conventional perturb and observe MPPT controller is used in this case, the details of which are given in Appendix 2. Then it is fed
to an inverter through a DC link capacitor. The inverter converts DC into AC power at the desired voltage and frequency, to perform the output current control. One of the important in the development of a single phase inverter for PV application is the DC-link capacitor. The DC link contains power pulsation, so that the capacitor should be connected to absorb this pulsating power to reduce the DC-link voltage ripple. The value of the DC-link capacitor is calculated by the equation (6.1).

\[
C_{dc} = \frac{P}{2\omega V_{dc} V_{ripple}} 
\]  

(6.1)

where \( P \) is the Power, \( \omega \) is the output AC voltage frequency, \( V_{dc} \) is the nominal DC voltage and \( V_{ripple} \) is the maximum allowed ripple voltage.

6.3. MODEL OF AN INVERTER

The model of the DC-AC converter is needed to simulate the circuit and to analyze its behavior. Figure 6.2(a) shows the circuit diagram of a DC-AC single phase full bridge Inverter.
Figure 6.2. (a) Circuit diagram of a DC-AC inverter, (b) PWM signal for a DC-AC inverter

The PV inverter is designed for 230V, 50 Hz. The DC voltage which is obtained from the converter output is given to the inverter, for converting it to a smooth sinusoidal waveform. An inductor current flowing through filter, and load voltage are considered as state variable. The state equations with S1 and S3 ON (d interval) and S1 and S3 OFF (1-d interval) are expressed as:

\[
\frac{d i_L}{dt} = -\frac{1}{L} v_0 + \frac{1}{C} i_L - \frac{1}{RC} v_0 + \frac{1}{L} v_S \quad (6.2)
\]

\[
\frac{d i_L}{dt} = -\frac{1}{L} v_0 + \frac{1}{C} i_L - \frac{1}{RC} v_0 - \frac{1}{L} v_S \quad (6.3)
\]

The basic operation of the dc–ac full-bridge switching converter is that each pair of switches, S1–S3 and S2–S4, are operated alternately for each switching period with their duty cycle (d). The duty cycle (d) is a ratio of an ON time (t_on) to a switching period (T), d= t_on /T = t_on f_s, as shown in Figure 6.2 (b).
6.4 CONTROL OF THE SOLAR PV INVERTER

The principle of the Synchronous Reference Frame (SRF) is illustrated in Figure 6.3. The SRF method is used to extract the reference current from the grid connected load current. In this method the load current is transformed into a conventional rotating frame dq. Here, $\theta$ is the transformation angle that represents the angular position of the reference frame. The reference frame rotates at a constant speed, in synchronism with the three phase AC voltage. To implement this method, a synchronizing system like the Phase Locked Loop (PLL) is used. A High Pass Filter (HPF) is used to eliminate the harmonic content. Any one of the three phase reference currents is then used for the adaptive hysteresis current band calculation.

The performance of the power inverter depends on the control strategy adopted to generate the gate pulses. As the photovoltaic arrays are in good approximation to a current source, most of the photovoltaic inverters are voltage-source inverters. To control the voltage-source inverters, current control methods are normally used. There are several current control strategies proposed, namely, the Average Current Mode Control (ACMC), Sliding Mode Control (SMC) (Azizur Rahman et al 1997) and hysteresis
control (Anushuman Shukla et al 2007). Among the various current control techniques, hysteresis control is the most popular one for a voltage source inverter. The conventional Hysteresis controller is a fixed hysteresis band controller. This is very simple, has a robust current control performance with good stability, very fast response, an inherent ability to control peak current, and is easy to implement. The hysteresis band is used to control the load current and determine the switching signals for inverter gates. When the load current exceeds the upper band, the comparators generate control signals in such a way as to decrease the load current and keep it between the bands, as illustrated in Figure 6.4.

![Figure 6.4 Hysteresis current controller concepts](image)

The fixed hysteresis band method has the drawbacks of variable switching frequency, heavy interference, harmonic content around the switching side band, and irregularity of the modulation pulse position. These drawbacks result in high current ripples and acoustic noise. To overcome these undesirable effects, this work presents an adaptive hysteresis band control. This controller adjusts the hysteresis bandwidth, as a function of the reference compensator current variation, to optimize the switching frequency and THD of supply current. Switching frequency varies with respect to the band size, the inverter and the grid parameters.
Figure 6.5 Principle of the adaptive hysteresis current controller concept

Figure 6.5 shows the concept of the adaptive hysteresis current controller where the ascendant and descendant slopes of the inverter reference current compensator are produced by imposing voltage stresses $+V_{dc}$ & $-V_{dc}$ on an inductor, which connects the inverter to the grid.

The equation for the hysteresis bandwidth is given below as: (Xunjiang Dai, Qin Chao, 2009):

$$HB = \frac{1}{2Lf_s} \left( V_s + L \frac{di_{ref}}{dt} \right) \left[ 1 - \frac{1}{V_{dc}} \left( V_s + L \frac{di_{ref}}{dt} \right) \right] \quad (6.4)$$

Equation (6.4) defines the hysteresis band that depends on the system parameters. By substituting the desired switching frequency, the hysteresis band value is obtained. Hence, the algorithm that adaptively adjusts the hysteresis band width based upon electrical parameters, with the purpose of maintaining constant switching frequency, is known as the adaptive hysteresis current controller.
6.5 SIMULATION OF A PV SYSTEM WITH ADAPTIVE HYSTERESIS CURRENT CONTROL

6.5.1 Test System Details

The test system considered here, is a grid connected 3.3 kW PV system. The system has a PV array, a DC-DC converter, a DC link Capacitor, and a DC-AC inverter. The PV system is simulated, using the two-diode model of the PV cell in Matlab/Simscape software. Each module consists of 36 photocells, connected in series. The nine PV modules are connected in parallel with another set of nine PV modules, to provide a 3.3kW single phase PV system. The system parameters used in this simulation are presented in Table 6.1.

<table>
<thead>
<tr>
<th>Table 6.1 Parameters of the PV array</th>
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<tbody>
<tr>
<td>Number of Parallel PV array ($N_p$)</td>
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<tr>
<td>Number of PV array in Series ($N_s$)</td>
</tr>
<tr>
<td>Open circuit Voltage ($V_{oc}$)</td>
</tr>
<tr>
<td>Short circuit current ($I_{sc}$)</td>
</tr>
<tr>
<td>Watt peaks ($P_m$)</td>
</tr>
<tr>
<td>Optimum operating current ($I_{mpp}$)</td>
</tr>
<tr>
<td>Optimum power voltage ($V_{mpp}$)</td>
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The passive elements of the inverter used in this work are shown in Table 6.2.

<table>
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<tr>
<th>Table 6.2 Parameters of the DC-AC inverter</th>
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<tr>
<td>Load Resistance</td>
</tr>
<tr>
<td>Load Inductance</td>
</tr>
<tr>
<td>Capacitors</td>
</tr>
<tr>
<td>Dc link capacitors</td>
</tr>
</tbody>
</table>
The simulated PV system is connected to grid. The grid connection is achieved by connecting AC voltage supply. In hardware the implementation prototype is connected to load. The parameters of the Grid are:

- Grid Frequency = 50 Hz
- Peak voltage = 390 V
- Grid Resistance = 0.012 ohm
- Grid Inductance = 3.056e-4 Henry

Figure 6.6 shows the simulink of the developed PV array along with the DC-DC converter, DC-AC inverter, and their proposed controllers. Matlab/simulink is shown in Figure 6.7 shows the adaptive hyteresis current controller developed in Matlab/Simulink. The perturb and observe MPPT controller and modified incremental conduction algorithm simulated in Matlab/simulink are shown in Figure 6.8.

Figure 6.6 Overall PV system configurations developed in Matlab/ Simulink
Figure 6.7. Adaptive hysteresis current controller developed in Matlab/Simulink
6.5.2 Results and Discussion

The performance of the proposed algorithm is tested under two different conditions: (i) Under uniform irradiation (1000 W/m²) and Temperature (55°C), (ii) Under varying irradiation conditions of 1000 W/m² to 700 W/m² and temperatures of 55°C to 35°C.

6.5.2.1 Performance of the proposed algorithm under uniform condition

Here, the PV System is simulated along with the inverter, which is controlled by the proposed adaptive hysteresis current control. The DC link voltage, inverter output voltage, and current obtained, are shown in Figure 6.9 (a), (b) and (c).
Figure 6.9  (a) DC link voltage, (b) Inverter Current and (c) Inverter voltage

The THD and switching frequency in this case are shown in Figure 6.10 (a) and (b).
Figure 6.10  (a) THD level of the adaptive hysteresis controller of the photovoltaic inverter, (b) Switching frequency of the adaptive hysteresis controller of the photovoltaic inverter

The THD in this case is 3.14%. Also, the modulation frequency is maintained constant at 5 kHz, as shown in Figure 6.10. The current has a low total harmonic distortion, and a constant switching frequency.

For comparison, the inverter was controlled using a sinusoidal PWM, and fixed hysteresis current control techniques. The load current harmonic spectrum and its switching frequency of sinusoidal PWM controlled inverter are shown in Figure 6.11 (a) and (b). The total harmonic distortion (THD) in this case is 7.81%. Also, it is observed from Figure 6.11, that the switching frequency varies over a wide range. The sine PWM which is
otherwise called as carrier based PWM technique compares low frequency sine (modulated) wave with the high frequency triangular (carrier) wave. This generates varying pulse width which leads to variable switching frequency. Figure 6.12. shows the output current, harmonic current and the switching frequency, in the case of the fixed hysteresis band controller. The fixed hysteresis control method builds fixed band for current tracking, hence the switching speed becomes variable which leads to variable switching frequency. Table 6.3 gives the average switching frequency, and the percentage THD values of load current with different techniques. From this table it is observed, that the switching frequency is constant and THD is minimized in the proposed technique.

Figure 6.11 (a) THD of the photovoltaic inverter sinusoidal PWM, (b) Switching frequency of the photovoltaic inverter sinusoidal PWM
Figure 6.12 (a) THD level of the fixed hysteresis controller of the photovoltaic inverter, (b). Switching frequency of the fixed hysteresis controller of the photovoltaic inverter

Table 6.3 Results of various techniques

<table>
<thead>
<tr>
<th>Current control Technique</th>
<th>THD %</th>
<th>Average switching frequency (kHz)</th>
</tr>
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<tbody>
<tr>
<td>Adaptive Hysteresis band</td>
<td>3.14</td>
<td>5</td>
</tr>
<tr>
<td>Fixed Hysteresis band</td>
<td>6.93</td>
<td>2.26</td>
</tr>
<tr>
<td>Sinusoidal PWM</td>
<td>7.81</td>
<td>3.28</td>
</tr>
</tbody>
</table>

According to the IEEE 519-1992 standard, the THD value of the voltages should not exceed 5%. Table 6.3 shows that the THD value of the output voltage is acceptable by the IEEE standard.

6.5.2.2 Robustness of the proposed algorithm to irradiation and temperature changes

In order to verify the robustness of the proposed algorithm, the input of the PV array solar irradiation and temperature are varied, to represent
the varying atmospheric conditions. It is assumed that the PV array initially receives a uniform irradiation of 1000 W/m² and the temperature is 55°C. A step change in the irradiation level (from 1000 and 700 W/m²) and temperature (from 55°C to 35°C) are applied at $t = 0.3$ s. The DC link voltage and inverter current waveform for this case, are shown in Figure 6.13 (a-d).
From Figure 6.13, it is observed that up to $t=0.3$ s, the DC link voltage is maintained at 400 V. The changing irradiation and temperature (at $t=0.3$ s) produce oscillations in the dc link voltage initially; after a short moment it retains the voltage of 400 V. But it is observed that the sudden partial shading effect at $t=0.3$s decreases the inverter current. The switching frequency in this case is almost constant, as in the case of a uniform atmospheric condition.

6.6. FPGA REALIZATION OF THE PROPOSED INVERTER CONTROL

To verify the performance of the adaptive hysteresis current controller, experimental studies were conducted on the prototype of the power conditioning system. The developed prototype is composed of a single phase inverter, and a Spartan 3 xilinx FPGA development board. Figure. 6.14 show the experimental setup.
The proposed algorithm is executed in FPGA and its output gate pulses are shown in Figure 6.15 (a). The snapshot of the input and output port assignment is also depicted in Figure 6.15 (b).
The output waveform of the voltage and current is shown in Figure 6.16.

(a)

Figure 6.16 (a) Inverter output voltage (upper) and current (lower) waveform, (b) THD of the inverter output voltage waveform

(b)

Voltage=20v/div, Current=500mA/div, Time=5ms/div, THD=5.59%

The THD of the output voltage is 5.59%. The THD in the experimental waveform is higher, when compared to the simulated one, which can be further reduced by a more accurate selection of the LC filters used.
6.7 CONCLUSION

This chapter has presented an inverter controller for the grid connected PV system. The adaptive hysteresis current controller is used to control the DC-AC inverter. The proposed algorithm for the inverter controller has been tested on a 3.3 kW PV array of a grid connected PV system in Matlab/ simulink simulation and FPGA based hardware prototype. Based on the observation of the simulation and experimental results, the developed algorithm is found to be very efficient, in terms of the constant switching frequency and lesser THD value. The proposed current control algorithm overcomes the difficulties and limitations, especially the variable switching frequency, encountered by conventional approaches.